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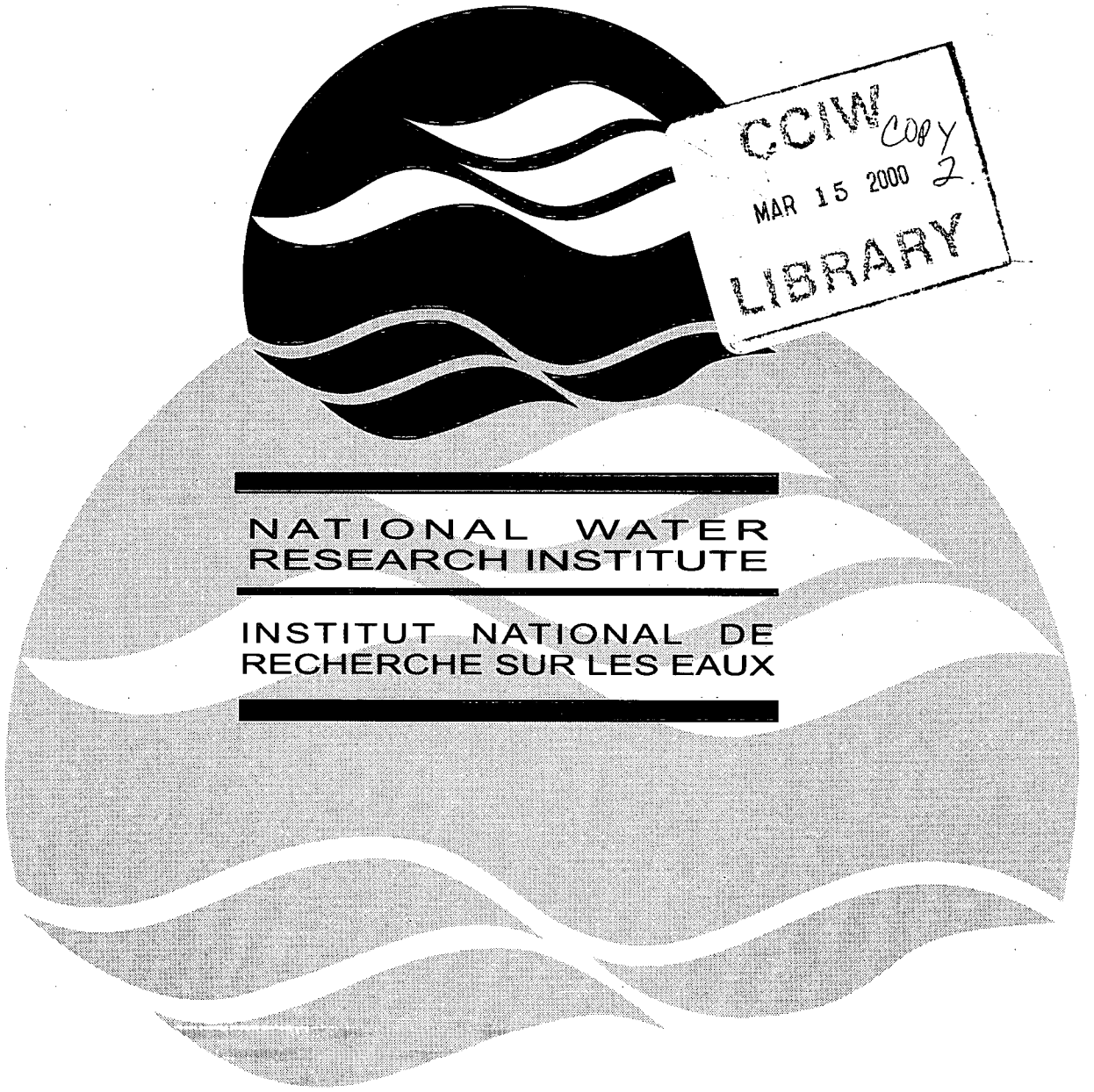

ASSESSMENT AND REMEDIATION OF CONTAMINATED SEDIMENTS - A NORTH AMERICAN PERSPECTIVE

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MANAGEMENT PERSPECTIVE

This invited paper was presented at the NATO Advanced Research Workshop "Environmental Reconstruction in Headwater Areas", held at Liberec, Czech Republic, November 24-28, 1997. The paper will be published in a book by Kluwer (NATO ASI Series).

The topic of this paper relates to Federal/Departmental Issue 4 - Conserving Ecosystems, Issue 4.1c - Great Lakes Action Plan and Remedial Action Plans, and Issue 4.2a - Mining Regulations.

The fields of contaminated sediment assessment and remediation have matured significantly over the last decade. Experience from the Canadian and U.S. Areas of Concern (AOCs) in the Great Lake Region indicates that sediment remedial projects are very costly and remedial costs increase rapidly with increasing levels of cleanup.

Sediment quality guidelines should incorporate not only physical and chemical measurements but also biological endpoints. The use of in-situ remediation techniques, either in-situ isolation or in-situ treatment, is likely the only solution for remediating large volumes of contaminated sediments occurring in many AOCs.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Cette communication a été présentée dans le cadre de l'atelier de recherche avancée de l'OTAN intitulé « Restauration de l'environnement dans les secteurs d'amont », qui a eu lieu à Liberec, en République tchèque, du 24 au 28 novembre 1997. Elle sera publiée dans un ouvrage de Kluwer (NATO ASI Series).

Le sujet de cette communication porte sur le thème 4 « La conservation des écosystèmes », le thème 4.1c - Le Plan d'action des Grands Lacs et les plans d'assainissement, et le thème 4.2a - Le *Règlement sur l'exploitation minière*.

L'évaluation et l'assainissement des sédiments contaminés ont beaucoup évolué au cours de la dernière décennie. L'expérience acquise dans les secteurs préoccupants (SP) de la région des Grands Lacs au Canada et aux États-Unis révèle que les projets de dépollution des sédiments sont très coûteux, et que les coûts de la dépollution augmentent de façon proportionnelle au niveau de dépollution requis.

Outre des mesures chimiques et physiques, les lignes directrices relatives à la qualité des sédiments devraient incorporer des variables biologiques. L'utilisation de techniques de dépollution *in situ*, qu'il s'agisse de l'isolement ou du traitement, est probablement la seule solution pour assainir des volumes élevés de sédiments contaminés dans bon nombre de SP.

RÉSUMÉ

Ce rapport de synthèse présente une vue d'ensemble mais sélective des recherches multidisciplinaires récentes portant sur l'évaluation et la dépollution des sédiments contaminés dans la région des Grands Lacs. Dans bon nombre de ports et de voies interlacustres des Grands Lacs, les sédiments sont fortement contaminés par les nutriments, les métaux et les substances organiques persistantes associés aux rejets industriels, agricoles et urbains ainsi qu'aux dépôts atmosphériques. Le rapport fait souvent référence au port de Hamilton, dans le lac Ontario, où des sédiments très contaminés par un mélange complexe de métaux, de matières organiques et de nutriments ont fait l'objet d'études intensives, et où plusieurs techniques d'assainissement *ex situ* et *in situ* ont été soumises à des essais pilotes. L'expérience acquise à cet endroit et ailleurs au Canada et aux États-Unis révèle que les projets de dépollution des sédiments sont très coûteux et que les coûts de la dépollution augmentent de façon proportionnelle au niveau de dépollution requis. L'adoption de mesures efficaces pour éliminer la pollution de sources diffuses et ponctuelles est essentielle pour assainir le milieu à long terme. Des efforts simultanés doivent être déployés afin de réduire la pollution à la source et de mettre au point des techniques de dépollution à la fois rentables et respectueuses de l'environnement et d'en faire la démonstration.

ASSESSMENT AND REMEDIATION OF CONTAMINATED SEDIMENTS - A NORTH AMERICAN PERSPECTIVE

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ABSTRACT

This review article presents a broad, though selective, overview of recent multidisciplinary research concerned with the assessment and remediation of contaminated sediments in the Great Lakes region. Sediments in many harbours and connecting channels of the Great Lakes are severely polluted with nutrients, metals and persistent organic substances due to industrial, agricultural and municipal discharges and atmospheric deposition. The article frequently refers to Hamilton Harbour, Lake Ontario, where sediments severely contaminated with a complex mixture of metals, organics and nutrients have been intensively studied, and also several ex-situ and in-situ remedial technologies have been tried in pilot-scale tests. Experience from this location, as well as from other sites in Canada and the U.S., indicates that sediment remedial projects are very costly and remedial costs increase rapidly with increasing levels of cleanup. Effective measures to eliminate pollution from both point and diffuse sources are a prerequisite for any long-term successful remediation. Combined effort is required to fight pollution at the source, and to develop and demonstrate environmentally sound and cost-effective remedial technologies.

1. Introduction

Contaminated sediments may pose risks to both human health and to healthy sustainable environment. Direct links have been established between sediment-bound contaminants and adverse impacts on aquatic biota and wildlife species. Well-documented cases of acute catastrophic human poisoning due to fish and shellfish consumption were linked to the occurrence of toxic metals discharged into the aquatic environment [1]. Very little is known about the long-term effects of contaminated sediments on humans, but it is clear that toxic organic chemicals and metals are a threat to the entire ecosystem [2]. Benthic invertebrates are in direct contact with sediments and thus they demonstrate the first impact of contaminants, including acute toxicity, deformities and alterations in genetic structure. The uptake of persistent bioaccumulating substances by benthic organisms and their retention and buildup in the food chain are of concern. Neoplasms in mollusc and in bottom-feeding fish have also been associated with sediment contamination. Concerns have been expressed regarding the occurrence of carcinogens in contaminated sediments and their potential effects on humans consuming fish from contaminated areas or engaging in water-contact activities.

Contaminants are bound typically, but not always, with the fine-grained fraction of sediments, and are therefore frequently found in low-energy aquatic bodies in urban regions such as industrialized harbours, urban lakes, dams and river mouths. Flood waters in rivers deposit contaminated sediments on agricultural land in alluvial plains and these subaerially exposed sediments pose risks to local ecosystems and also endanger the quality of groundwater. In the Great Lakes region, the International Joint Commission (IJC) identified 43 Areas of Concern (AOCs), which all have problems associated with the occurrence of contaminated sediments [3,4,5]. Apart from direct and most serious ecological problems, contaminated sediments are a key obstacle in restoring important beneficial uses in the AOCs. Fish consumption advisories adversely affect sport and commercial fishing industries. Restrictions on maintenance dredging threaten the viability of many commercial ports. Where maintenance dredging is permitted, existing regulations stipulate the disposal in some form of a confined disposal facility (CDF), which is significantly more expensive than open-water disposal. During the period from 1985 to 1989, over 5 million m^3 of sediment were dredged in the Great Lakes and 51 % of this volume (about 3 million m^3) had to be stored in CDFs. Increased costs are incurred by treating water drawn from contaminated areas [5].

2. Physical and chemical properties of sediments

Fine-grained sediments consist of inorganic sediment particles (e.g. clay minerals, quartz, feldspars, carbonates), amorphous coatings on sediment particles of various composition (e.g. Fe and Mn oxides and hydroxides), and organic matter that may reach up to 10 % of the sediment solid phase. Interstitial pore water may comprise up to 90 % of the total sediment volume in the proximity of the water-sediment interface. Typically, sediment moisture content gradually decreases with depth due to the process of self-weight consolidation. Gases such as methane or nitrogen, produced by the decomposition of organic matter (methanogenesis and denitrification), are frequently found in fine-grained organic sediments [6].

Common sediment contaminants that pose risks to human and/or environmental health include halogenated hydrocarbons (PCBs, dioxins, many pesticides), polycyclic aromatic hydrocarbons (PAHs such as naphtalene, pyrenes, etc.) and trace metals (including Cd, Ni, Cr, Cu, Pb, Zn and Hg). Many organic contaminants degrade with time but the rates of degradation are generally slow. Metals, as elements, do not degrade.

Leaching of nonpolar organic contaminants is determined primarily by the amount of organic carbon fraction present in the sediment. Partitioning between sediment solid phase and water phase is given by:

$$K_p = C_s/C_w \qquad (1)$$

where K_p is the partition coefficient; C_s is the contaminant concentration in the solid phase and C_w is the concentration in the water phase. Usually, the partition coefficient is normalized with respect

to organic carbon content:

$$K_{oc} = K_p/f_{oc} \quad (2)$$

where K_{oc} is the organic carbon normalized partition coefficient and f_{oc} is the fraction of organic carbon present in the sediment. K_{oc} can be predicted from chemical solubility in water or the octanol/water partition coefficient, K_{ow}. Several empirical relationships have been developed between K_{oc} and K_{ow} [7].

It should be realized that the above relationships were mostly established in the laboratory under controlled conditions and with pure organic chemicals, as opposed to impure mixtures and variable conditions occurring in the field. Several studies, which have investigated partioning of organic contaminants, have identified significant differences between laboratory-derived and field results [8,9]. Also it is now clear that using the equilibrium partitioning theory may lead to the underestimation of contaminant bioavailability in the case of sediment-feeding benthos both in marine and freshwater environments [10,11,12]. Thus, the direct uptake from sediment particles can be an important additional source for sediment-feeding benthic invertebrates.

Mobility of metals is dependent on chemical and physical reactions and factors such as oxidation status, pH, temperature, adsorption, sedimentation, complexation, precipitation and grain size [13]. In addition, a variety of common sediment bacterial communities can metabolize and alter metal/metalloid valence states and thus alter the bioavailability and toxicity of metals. This is particularly true for the microbial transformation of mercury compounds to the poisonous and bioaccumulative methylmercury [1,14]. The portion of metals dissolved in pore water, or bound by cation exchange processes to clay minerals and humic material, is considered to be most bioavailable to organisms. Potentially bioavailable are metals adsorbed to carbonates, metal oxides and hydroxides, metals chelated with humic substances, and metals precipitated as sulphides. Unavailable to the environment are metals within the crystalline lattice structure of clay minerals [15]. Mobility of metals can be further strongly influenced by the presence of sulphides, in particular acid volatile sulphide (AVS), defined as the gaseous sulphide evolved upon addition of cold acid to the sediment [16]. It is of interest to determine with the evolution of gaseous AVS the molar metal content referred to as simultaneously extracted metals (SEM). The molar ratio of SEM/AVS is used to evaluate the potential for mobility and toxicity of trace metals in sediments. Thus, if the ratio is larger than unity, mobility of metals may be expected, which will also be reflected in metal pore water concentrations. If SEM/AVS is less than unity, the metals can be expected to be immobilized as sulphides. It is clear, however, that AVS is not the single major factor controlling metal bioavailability, and other factors (e.g. Fe and Mn oxides and hydroxides) may be of great importance [17].

Mine waste piles and tailing ponds are common important sources of contamination for aquatic environments, typically due to the release of metals and radioactive substances. A particular and very frequent problem is the oxidation of sulphide minerals (e.g. those of Pb, Cu, Ni, Zn and Ag). The reaction yields sulphuric acid, which increases the mobility of trace metals. Acid mine

drainage also occurs in coal mining when coal or host rock material contains significant amounts of pyrite. Subaerial exposure of pyrite leads to pyrite oxidation, a complex chemical and microbiological reaction, which results in a drastic lowering of pH with all its undesirable ecological effects [18]. These effects are particularly severe in regions where carbonate rocks or soils are scarce and thus water has a lower buffering capacity to neutralize acidic discharges.

3. Sediment Toxicity Assessment

Assessing the toxicity of sediments is an important but complex step required in sediment remediation strategy. Due to the nature of contaminant association with aquatic sediments, chemical concentrations alone do not necessarily indicate contaminant bioavailablity. Chemical sediment quality criteria alone do not provide an empirical evidence that contaminants are bioavailable and biologically damaging. For this reason, chemical analyses should complement rather than replace direct bioassay measurements. Biological sediment quality guidelines are being developed, but there is still insufficient information for many AOCs on direct biological impacts on aquatic biota [19]. A number of biological sediment quality criteria have been developed [15]. Bulk sediment toxicity tests are carried out to expose test organisms to sediments usually containing several potentially toxic chemicals. At the end of a given time period, the response of an organism is examined in relation to a specified biological endpoint. Spiked-sediment toxicity tests are carried out to determine the dose-response relationship of selected organisms to sediments that have been spiked with known amounts of contaminants or mixtures of contaminants. The use of the Sediment Quality Triad [20,21] was suggested, in which sediment contamination is quantified by chemical analyses, sediment toxicity is determined by laboratory bioassays, and in-situ benthic community structure is described by means of taxonomic analyses. The data from the three methods are complementary and can be used to discriminate conditions of minimal, uncertain and major biological impacts. The choice of test organisms in bioassays is important. The bioassays should preferably use indigenous sediment-dwelling species. One of the most widespread benthic groups, which is ubiquitous in freshwater aquatic habitats, is an oligochaete worm, particularly *Tubifex tubifex*, which is cosmopolitan in distribution and forms an important component of the Great Lakes benthic community [22]. Sediment toxicity mapping for all of Hamilton Harbour has been carried out using *T. tubifex* reproduction relative to clean reference sites [23]. Other benthic organisms used for bioassays at NWRI include the chironimid, *Chironomus riparius*, the amphipod, *Hyalella azteca*, and the mayfly, *Hexagenia limbata*. The initial sediment toxicity testing emphasized acute tests (survival of test organisms). Recently, chronic toxicity, with end points such as growth and reproduction, has also been examined, as it provides more sensitive and discriminatory measurements of biological effects [24]. It has been recently argued that generalizations regarding sediment pollution status are not (yet) possible, and sediment quality assessments are primarily a function of the correct reference comparison [17].

4. Field and Laboratory Methods

4.1 MAPPING OF CONTAMINATED SEDIMENTS

Mapping the distribution and thickness of contaminated sediments is carried out by offshore coring and grab sampling using a variety of sediment sampling devices [25]. As contaminated sediments are typically of very similar texture as clean sediments, it is often difficult to determine the volume of contaminated sediments from sedimentological or geotechnical sediment properties. Due to the complex pattern of contamination occurring in sediments, the use of geophysical techniques is helpful to complement the information obtained from isolated cores and samples. Magnetic susceptibility has been used to map contaminated sediments in Hamilton Harbour [26,27]. The mapping was based on a demonstrated relationship between increased sediment magnetic susceptibility and contamination due to industrial processes and urbanization that contains non-toxic spherules of magnetite associated with construction materials, steel industry discharges, coal fly-ash and car emissions. The extent of sediment disturbance due to shipping, dredging and dumping in Hamilton Harbour was determined by a side-scan survey [28,29]. The side-scan survey revealed prominent morphological features of the harbour floor that would not be detected by an underwater camera due to very poor visibility in the deeper portions of the harbour. In Hamilton Harbour, the impacts of sediment disturbance due to ship traffic have also been investigated by water column profiling, suspended sediment sampling and in-situ flume experiments [30]. An acoustic bottom-classification system called RoxAnn™ was used in the St. Lawrence River at Cornwall, Ontario, in an area known to have a very complex pattern of fine-grained contaminated sediments intermixed with coarser deposits [31]. This technique was also used successfully to map the horizontal extent of a sand cap placed over contaminated fine-grained sediments during an in-situ capping project in Hamilton Harbour [32].

4.2 SEDIMENT SAMPLING METHODS

The comprehensive handbook by Mudroch and MacKnight [25] provides an excellent coverage of existing sampling devices used in North America for sampling contaminated suspended and bottom sediments and sediment pore water. Proper sediment handling must be considered a very important step for subsequent physical, chemical and biological testing. Unless sediment samples are carefully collected, laboratory testing may yield incorrect results. Samples of very soft fine-grained sediments for geotechnical testing should be disturbed as little as possible, and therefore large box corers are preferable to gravity corers or grab samplers.

Sediment samples should be separated from the collection devices and transported in plastic, polyethylene, or glass containers. Samples that contain volatile compounds should be refrigerated at 4° C or kept on ice to prevent further volatilization [15]. Sediments contaminated with organic compounds should be transported in brown, borosilicate glass containers with Teflon lid liners. Polyethylene, Teflon, or glass containers are recommended for samples to be analysed for

inorganic chemicals. The prime disadvantage of glass containers is that they easily break in the field, particularly when the samples are frozen. Sediments for biological testing can be collected, transported and stored in plastic or glass containers [25].

The collection of sediment pore water should be carried out in conjunction with sediment toxicological assessments. The oxidation of sediments brings about rapid changes of redox-sensitive species, which are dissolved in the pore water. For this reason, during pore water sampling it is critical to maintain the oxygen-free atmosphere. Iron and Mn are known to be extremely sensitive to oxygen exposure [33]. Collection of the sediment pore water can be obtained by squeezing, centrifugation followed by filtration, and by the use of in-situ dialysis membranes or "peepers". The preparation of the peepers and collection of the sediment pore water from the peepers is described in detail by Rosa and Azcue [34]. The peeper methodology does not yet permit the determination of dissolved organic contaminants due to the very low concentrations, which would require much larger samples of pore water than those obtained from the peepers.

5. Remedial Alternatives

An effective source control of pollution is a prerequisite to any successful sediment remediation. Basic options for remediation of contaminated sediments are: natural recovery (a no-action alternative), enhanced natural recovery by increased sedimentation, in-situ containment (in-situ capping and armouring), in-situ treatment, removal (using precise environmental dredging) and ex-situ containment, and removal and ex-situ treatment. Due to large volumes involved, the removal of in-situ contaminated sediments by dredging is in many cases neither economically feasible nor environmentally acceptable. Although treatment technologies are often effective in pilot-scale projects, the large volume of sediments to be treated make full-scale remediation projects in many cases prohibitively expensive. Each sediment remediation strategy must be considered on a site-specific basis, taking into account scientific, technical, regulatory and economic considerations.

Detailed guidelines on the selection, design and implementation of sediment remediation technologies have been developed under the Assessment and Remediation of Contaminated Sediments (ARCS) program [35]. This comprehensive technical document provides descriptions of available remediation technologies, examines decision-making strategies, estimates contaminant losses during remediation, and provides information about project costs. Relative costs associated with some commonly proposed techniques have been evaluated by Averett [36], based on the extensive experience of the U.S. Army Corps of Engineers. The evaluation shows an exponential increase in relative costs with an increased level of remediation effort (in-situ capping, CDF disposal, CDF disposal with controls, particle separation, solidification, biotreatment, extraction and incineration).

5.1 NATURAL RECOVERY AND ENHANCED RECOVERY

In certain cases, natural recovery may be the best option. Natural recovery includes the cumulative physical, chemical and biological processes that result in a reduction of contaminant concentrations [37]; e.g. gradual burial of contaminated sediments by fresh clean sediments, natural biodegradation of organic compounds, and mixing of old and new sediments by bioturbation. The natural process of sediment deposition can be accelerated by the addition of a thin (approx. 15 cm) cap, a process that is referred to as enhanced natural recovery [37]. In other cases, however, especially in riverine environments and in harbours adjacent to large lakes, it is imperative to confine contaminated sediments quickly in order to prevent contamination of much larger areas. An example of this problem is the large-scale migration of mirex (an insecticide and a fire retardant) from the Niagara and Oswego rivers into Lake Ontario. The major source of mirex local contamination was the Hooker Chemical Plant in Niagara Falls on the Niagara River. In the Oswego River, mirex was discharged into the river at an upstream location over a short period of time, and then gradually transported with sediments down the 14 km stretch of the Oswego River to Lake Ontario. The lake-wide distribution of mirex in Lake Ontario led, in part, to the subsequent closure of the Lake Ontario fishery [38]. Sediment remediation on the scope of mirex distribution in Lake Ontario is virtually impossible. The large-scale severe PCB pollution from small point sources is documented e.g. for the upper Hudson River in the New York State and for the Sheboygan River in Wisconsin [39,40].

5.2 IN-SITU SEDIMENT CONTAINMENT

Subaqueous in-situ capping (ISC) is the placement of clean (i.e. acceptable for unrestricted open-water disposal) material over an in-situ deposit of contaminated sediments. This remedial method has been investigated at NWRI as a pilot-scale demonstration in Hamilton Harbour [41,42], and project results indicate that ISC is a viable alternative both from economic and environmental considerations. Other pilot-scale and full-scale projects involving ISC have been undertaken around the world, particularly in the U.S. and Japan, and no contaminant migration trough sediment caps has been detected in long-term field monitoring. Armouring refers to the placement of a layer of riprap on the top of a cap to provide adequate protection against erosion due to flood flows, navigation effects and bottom currents. Comprehensive guidelines for the design of ISC projects include hydraulic, geotechnical, chemical and biological considerations, as well as monitoring requirements [43].

5.3 IN-SITU SEDIMENT TREATMENT

Sediments in lakes and reservoirs have been treated in-situ to control eutrophication using aluminium sulphate (alum), lime, calcite and ferric chloride [44, 45]. Dissolved calcium nitrate (an oxidant) mixed with nutrients has been injected at a controlled rate in contaminated sediments using a specialized injection equipment operated from a small vessel. This equipment has been used in several heavily polluted areas in Hamilton Harbour and at other sites for biodegradation of PAHs and total petroleum hydrocarbons (TPHs). The in-situ treatment resulted in significant

biodegradation of low molecular weight PAHs and moderate reduction of high molecular weight PAHs and TPHs [46,47].

5.4 SEDIMENT REMOVAL AND EX-SITU CONTAINMENT

Many industrial harbours require extensive maintenance dredging of contaminated sediments. These sediments have to be disposed of either in confined disposal facilities (CDFs) or in another underwater environment where they are covered with a layer of clean sediment (referred to as either level-bottom capping or contained aquatic disposal). One of the key requirements in dredging of contaminated sediments is the minimization of sediment resuspension. Precise positioning control (both horizontal and vertical) of sediment removal is also required. Silt curtains are typically required to confine sediment resuspension. These barriers are most effective in relatively shallow, quiescent water [35].

The disposal of contaminated sediments in the CDFs is the only proven method so far for full-scale sediment remediation in the Great Lakes region. The creation of wildlife habitats, such as CDFs, in areas of urban pollution has been questioned. Shoreline or upland CDFs are viewed as only temporary storage facilities. When unsorted dredged material is disposed in a CDF, the use of this man-made land is marginal due to poor dewatering and hence very low consistency of dredged material. As dredged material typically represents a heterogeneous mixture of different sediment particle size and water content, the material disposed in a CDF is highly prone to differential settlements. Furthermore, there are environmental concerns with CDFs associated with the uptake of contaminants by cover vegetation, soil invertebrates, waterfowl and other biota [4]. A management plan for a CDF requires both a competent geotechnical design and a comprehensive analysis of potential migration pathways due to physical, chemical and biological processes [48].

5.5 PRETREATMENT OF DREDGED MATERIAL

Pretreatment of dredged material is often carried out in order to separate coarser less contaminated sediment and to reduce the water content of dredged material. Effluent from the dewatering process requires industry wastewater treatment before it can be discharged into the aquatic environment. Extensive experience with sediment pretreatment has been documented both in North American and European literature [4,15,35,49]. The separation and pretreatment plant in Hamburg called METHA has been designed to separate and dewater up to 2 million m^3 of contaminated dredged sediment annually [49].

5.6 TREATMENT OF DREDGED MATERIAL

Numerous bench and pilot-scale ex-situ sediment treatment technologies have been investigated in the U.S. Assessment and Remediation of Contaminated Sediments (ARCS) program [35] and in the program sponsored by the Great Lakes 2000 Cleanup Fund of Environment Canada [50].

Destruction technologies examined included thermal destruction, chemical treatment and bioremediation. Separation technologies included extraction and thermal desorption. Immobilization and stabilization techniques were also examined. Research into the most promising and cost-effective technologies is ongoing. A need exists for the development of technologies capable of treating relatively large volumes of fine-grained sediments contaminated by a variety of inorganic and organic elements and compounds [4].

6. Regulatory, Legal and Funding Considerations

Any sediment remediation project, be it a demonstration pilot-scale project or a full-scale cleanup project, must address and comply with a number of legal and regulatory requirements. Comprehensive environmental assessments and reviews are required. In Canada, the environmental assessment procedures employed are as prescribed under the Federal Environmental Assessment and Review Process (EARP). Permits are required for specific remedial activities, including construction in waterways, discharge of dredged or fill materials, and emissions and discharges from sediment pretreatment and treatment processes.

In the U.S., most sediment remediation projects have been funded as a result of enforcement actions taken against polluters, typically industries or municipalities. In other areas, the Superfund has been responsible for sediment remediation [5]. The Superfund is a U.S. public trust fund and a nickname for a U.S. federal law (The Comprehensive Environmental Response, Compensation, and Liability Act), which was enacted in 1980. This law provides the authority through which the U.S. federal government can compel people or companies responsible for creating hazardous waste sites to clean them up. It further assists with the cleanup of inactive or abandoned hazardous waste sites where hazardous materials were either accidentally spilled or illegally dumped. In several U.S. AOCs, partnerships between government agencies, industry and municipal groups have been used as an alternative to enforcement actions [51].

In contrast to the U.S., enforcement in Canada has not been a significant source of funding for sediment remediation, and Canada has no direct counterpart to the Superfund. In the Great Lakes region, most sediment remediation projects have occurred through partnerships developed under Remedial Action Plans (RAPs) at AOCs, with the assistance of the federally-funded Great Lakes 2000 Cleanup Fund. This fund is a multiyear program that has sponsored (i.e. partially or fully funded) studies, demonstration and full-scale sediment remediation projects.

Major obstacles to sediment remediation both in Canada and the U.S. are: limited funding and resources, regulatory complexity, lack of a decision-making framework, insufficient research and technology development, and limited public and local support [5].

7. Conclusions

The fields of sediment assessment and remediation have matured significantly over the last decade. Sediment quality guidelines should incorporate not only physical and chemical measurements but also biological endpoints. Although novel sediment remediation techniques have been used with success elsewhere, sediment removal and disposal in a CDF remains the only proven full-scale technology in the Great Lakes region. The use of CDFs is, however, viewed as a temporary storage measure both for environmental and economic reasons. This approach may be appropriate for smaller volumes of acutely toxic sediments. Application of sediment treatment methods from hazardous waste sites has been found technically feasible at the pilot scale but very expensive at the full-scale level. The use of in-situ techniques, either in-situ capping or in-situ treatment, is likely the only solution for large volumes of contaminated sediments occurring in many AOCs. As contaminant concentrations in presently deposited fine-grained sediments are often significantly lower than in the past, natural or enhanced recovery may be appropriate for certain sites. The application of these low-cost techniques to harbours and navigable channels may be limited due to particle resuspension during storms, sediment mixing by bottom-dwelling organisms, requirements for maintenance dredging, and the ongoing disturbance of bottom sediments due to ship traffic. Follow-up multidisciplinary monitoring is required to determine environmental benefits obtained by remedial measures. Above all, significant sources of contamination, including both point and diffuse sources, have to be stopped before any costly full-scale sediment remediation is undertaken.

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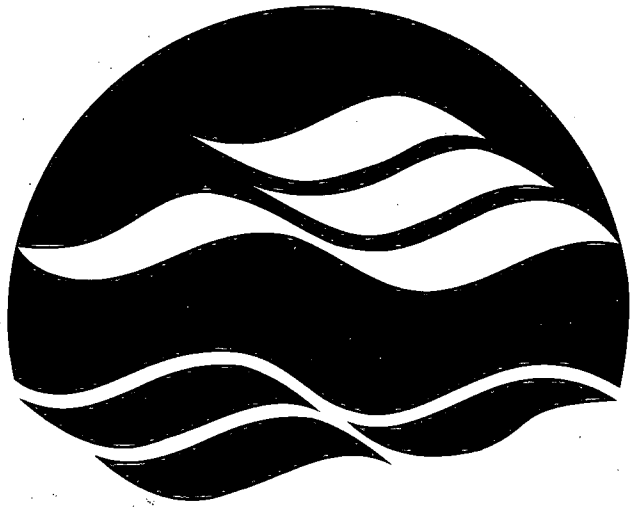

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